63-3-2

Refractomet Division

UNIVERSAL-CYCLOPS STEEL CORPORATION

(1)

Technical Report

401 127

(5)

Code-902 800

$4.60

Bridgeville, Pennsylvania

(6) MOLYBDENUM SHEET ROLLING PROGRAM

(9) > January 25, 1963,

Prepared Under Navy
Bureau of Aeronautics
(12) → Contract NOas 59-6142-c
(7) Interim Report No. 19,

Covering ~~Period~~
26 Oct~~ober 26, 19~~62 ~~to~~ 25 Janu~~ary 25, 19~~63,

(8) NA
(10) IV. incl. illus. tables
(11) NA
(13) NA

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ABSTRACT

This report covers details of work accomplished under Contract NOas 59-6142-c for the nineteenth reporting period. Ten sheets of .060" x 24" x 72" Mo+0.5%Ti have been produced. All sheet required for Phase II TZM rolling studies has been produced. Evaluation is approximately 90 per cent complete and a tentative rolling schedule for Phase III production has been selected.

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I Introduction

With resumption of InFab operation late in the last report period, sheet bars were hot forged for Mo+0.5%Ti Phase III production of .060" sheet. TZM sheet bars required for Phase II rolling variable evaluation were also forged. During this period the rolling of both materials was completed and evaluation approximately 90 per cent complete.

A meeting was held at the Bureau of Naval Weapons where the TZM evaluation was reviewed and a rolling practice for Phase III production tentatively selected.

An extension of this contract is presently required to permit completion of Mo+0.5%Ti production and initiation of work on the production of TZM (Phase III). The extension is in final stages of approval and it is anticipated that melting stock for TZM can be ordered during the first month of the next report period,

Equipment is presently being installed in InFab. Resumption of operation is scheduled for late February, thus, no delay is expected to result in forging the required sheet bar.

II Program Modifications and Additions

In a meeting held at the Bureau of Naval Weapons on December 27, 1962, the quantities and sizes of Phase III Mo+0.5%Ti and TZM production were finalized. Ten sheets .060" x 24" x 72" of Mo+0.5%Ti had been produced. The remaining extrusion stock on hand from the two ingots melted for Phase III (approximately half of each ingot) will be processed to .020" x 24" x 60" sheet. The following quantities of TZM sheet will be produced:

Size	No. Sheets	Sq. Feet	Weight
.016 x 18 x 60	100	750	640
.020 x 24 x 60	100	1000	1040
.040 x 24 x 72	27	324	689
.060 x 24 x 72	27	324	1031
Total	254	2398	3400

III Progress This Report Period (October 25, 1962 to January 25, 1963)

A. Mo+0.5%Ti Alloy, Phase III Production

Ten sheet bars forged during the previous quarter have been rolled to final gauge. Testing is expected to be completed within two to three weeks. Processing from ingot to sheet bar was documented in the previous reports. Evaluation of the material during the primary fabrication included chemical analyses (Interim Report No. 18) and a hardness survey on transverse discs from the middle of each of the extrusions as follows:

	VHN - 10 kg Load	
	KDTM-1126B	KDTM-1127B
End	186	193
1/2 Radius	191	198
Center	206	201

Samples were not cut from the forged sheet bar since the entire bar length was required for rolling.

During the forging operation, a camber occurred over the length of several of the sheet bars due to forging die wear. After trimming the bottom end and cutting the holder end from the bars, a press forge straightening operation from a 2200°F. hydrogen atmosphere furnace was employed to remove the camber. The sheet bar surfaces were thoroughly ground prior to rolling.

1. Sheet Rolling

   Table I outlines the rolling schedule which was followed to produce the ten .060" x 24" x 72" sheets. Table II lists the size of each piece at various rolling stages from sheet bar to rough sheared, as-rolled sheet. Initial rolling to .750" mold out was in the 4" sheet bar width direction. Following a recrystallization treatment and conditioning, rolling continued in the same direction to .260" mold out. The mold out was stress-relieved, trimmed to matching pairs and again surface conditioned at this point. Final rolling from a 1600°F. furnace was accomplished by rolling single pieces to approximately .110", matching the previously sheared pairs, reheating and rolling the pack of two to final gauge. All sheets have been given a final anneal of 2150°F. for one hour, descaled and trimmed to maximum size.

2. As-Rolled Gauge Survey

   Table III presents a gauge survey of the sheet in the as-rolled, descaled, rough sheared condition. Gauge variation within individual sheets ranges

from 2.5 mils to 6.0 mils. The sheets which exhibit higher vatiations generally contain a local heavy area which will probably be reduced by trimming to final dimensions. All sheets are sufficiently uniform and within a gauge range that will permit pickling 2 to 3 mils per side for surface contamination removal and still maintain a tolerance of .060 $\pm$ .003 inches.

3. Testing

Only two sheets to date have been pickled and sheared to final gauge and dimensions. Three pieces, 14" wide by 36" long, were cut from the two sheets and shipped to McDonnell Aircraft. The test reports for these sheets are included as Appendix A.

Due to a breakdown of high temperature vacuum tensile equipment, the 2000°F. tensiles were pulled late in January. As a result, the test properties followed shipment of the material by about seven weeks. The physical condition of the 24" x 72" sheets are presented in the appendix with the mechanical test results. Additional report sheets show the physical dimensions of the 14" x 36" panels cut from the sheets. Note that the flatness on the full sheets was within one per cent, Flatness of the 14" x 36" panels sheared from the sheets varied from 1-1/2—3-1/2 per cent. Reflattening in the final condition was not attempted. Maximum gauge variation in both the 24" x 72" and 14" x 36" pieces was .003 inches.

The 50 per cent recrystallization temperature as determined both metallographically and by hardness drop was 2250°F. Samples for this determination were taken from the stress-relieved sheet (one hour at 2150°F. stress-relief) and annealed an additional hour in hydrogen. Transition temperatures in the transverse direction were in the 0 to -50°F. range.

The 2000°F. tensile results were unexpected. The UTS in sheet 4 ranged from 83.3 to 87.2 ksi. In sheet 5 the range was 91.1 to 112.5 ksi. Previous 2000°F. tests on Mo+0.5%Ti were in the range of 55 to 65 ksi. Typical 2000°F. strength of TZM sheet is 80 to 85 ksi. Samples have been taken from the pulled test specimens and are being checked for hardness, microstructure and chemistry and additional specimens are being prepared in an effort to determine the reason for or justification of the results.

Excess length was rolled on these sheets in an effort to produce sufficient length to cut test material from locations as specified in the MAB document "Refractory Metal Sheet Rolling Panel Quality Sampling Specification" (MAB 184-M). This requires approximately 21" of length. As noted in Table II, the longest sheets in the two lots of material were approximately 83" long. Due to the small panel size requested by McDonnell, it was possible to sample according to MAB 184-M in sheets 1126B4 and 1126B5. It will not be possible to maintain this sample location and retain a 72" length on test sheets from 1127B.

Conditioning and testing of the remaining eight sheets will resume immediately on re-activation of the program.

4. Production of .020"Sheet

The remaining extrusion stock from ingots, KDTM 1126 and KDTM 1127, will be prepared for forging and processing which will be initiated with the start-up of InFab.

B. TZM Alloy - Phase II Rolling Studies

1. Hot Forged Sheet Bar

Sheet bars produced during the previous quarter were cut in half, conditioned and applied for rolling. Figure 1 is a transverse macrograph from one of the hot forged sheet bars. Edge ruptures similar to the ones visible in this macro occurred in several of the sheet bars while forging above 3400°F. A micrograph taken from this sheet bar (Figure 2) shows surface contamination. Analyses to positively determine whether this contamination is iron from the forging dies or interstitial contamination have not been taken since a thorough evaluation of this nature is being conducted on Contract AF33(657)-8495 (InFab Processing of TZM Sheet). This condition was not observed on sheet bars forged in earlier phases of this program.

In order to reduce stresses and substantial hardness variation noted in sheet bar forged in previous phases, these bars were heated to approximately

2800°F. for five minutes after forging. Hardness measured at six locations on the macro disc in Figure 1 averaged 236 DPH with a 230-243 DPH range.

2. Sheet Rolling

The rolling program consisted of producing two pieces of sheet nominally .060" x 12" x 24" following the schedule outlined in Figure 3. With the exception of the five variables in Figure 3 identified as "InFab", all rolling was conducted in air from gas-fired furnaces.

a. Air Atmosphere Rolling

Initial rolling of sheet bar was transverse to the forging direction. Rolling to .750" thick was from a 2200°F. furnace. Annealing at this point varied from 2450°F. to 2800°F. according to the outline in Figure 3. Figure 4 presents the hardness resulting from these various anneals. Material condition covered the range from stress-relieved to fully recrystallized.

The second rolling operation to .260" was in the same rolling direction and at the same temperature as the previous rolling operation to .750". Annealing temperatures at this point (2150°F., 2300°F., 2450°F.) were selected to result in three degrees of stress-relief. The highest anneal (2450°F) could, in some cases, produce traces of recrystallization.

Variables included in the final rolling operation were finish rolling temperature (1400°F., 1600°F., 1800°F.) and rolling direction i.e.: straight rolled—same as all previous rolling; and cross rolled—90 degrees to previous rolling. It will be noted that the major portion of the rolling was conducted at 1600°F. based on Mo+0.5%Ti results. Likewise, most variables were cross rolled. The rolled gauge was .065" to permit pickling to .060" prior to test to remove surface contamination.

Material has also been rolled to .020" sheet following the per cent reductions and temperatures of sheet numbers 2744, 2745, 2746 and 2753 through 2758 as shown in Figure 3.

b. InFab Rolling

The five variables included in the InFab rolling (Figure 3) involved rolling over the temperature range of 1800°F. to 2600°F. to final gauge. A 10 minute 2900°F. anneal at .750" and one hour at 2350°F. at .260" were performed in the InFab rolling mill furnace on all variables.

Figure 5 (Plate A) shows a grain boundary carbide condition found in areas of sheet bar 1096B5 (macro and micro of this sheet bar in Figures 1 and 2). This condition indicates heating to above 3150°F. in the final stage of forging

thus resulting in precipitation of grain boundary molybdenum carbides. The observers data sheet shows that the bar was heated to 3250°F. at 1-3/4" and forged lightly to 1-1/4". Plate B indicates that the condition persisted through the 2400°F. rolling operation to .750". Following a 2900°F. anneal at this point, the grain boundary carbides were not observed (Plate C). Table IV lists the hardness of the .750" and .260" mold out.

3. Sheet Evaluation - As-Rolled Material

Test blanks for all evaluation were warm sheared from the sheet in the as-rolled and descaled (molten hydride) condition. Following the devised hydrogen atmosphere anneal, blanks for mechanical tests were pickled .003" per side to remove surface contamination. Properties which have been determined are included in Table V.

Samples for hardness and micro examination were initially annealed for one hour over the 2200°F. to 2700°F. temperature range. Based on these results, additional material was annealed at 2300°F. and 2400°F. for tensile, bend transition, minimum bend radius, delamination tendency and flange test. Following this initial screening series, material for additional tests were prepared for more thorough evaluation of the material representing rolling variables which exhibited the best combination of properties.

The .020" sheet rolling schedule trailed the .060" material by several weeks. Evaluation of this sheet has just recently been initiated.

a. Hardness and Recrystallization

The as-rolled hardness and response to heat treatment has been related to rolling variations in Figures 6 through 9. The hardness curves in Figure 6 represent the average of all variables annealed for one hour at .750" mold out at the temperatures shown. The effect of this intermediate anneal (ranging from stress-relieved to recrystallized mold out) on the hardness of the finished .060" sheet is evident. Increasing hardness occurred with increasing amounts of retained work in the mold out. The effect on recrystallization was not as pronounced, however, since metallographic examination indicated trace to 10 per cent recrystallization in the 2400°F. annealed condition in all cases. Estimates of recrystallization at 2500°F. and 2600°F. were somewhat lower than would be expected from the hardness curves. As noted in Table V, as little as 40 per cent recrystallization was estimated in the 2600°F. annealed condition. Full recrystallization was noted only in material annealed at 2800°F. at .750" sheet bar.

Response to annealing as related to percentage of cold work is shown in Figure 7. With the

exception of the 96 per cent worked material, the curves represent material which received a 2700°F. anneal at .750" mold out. Again, the hardness level is directly related to the cold work.

Figure 8 curves represent the average hardness of sheet rolled from 2700°F. annealed .750" mold out at three finish rolling temperatures. There appears to be little or no significant effect of stress-relief temperature at .260" mold out over the range of 2150°F.—2450°F. on the hardness properties of finished sheet. Likewise, finish rolling temperature (Figure 9) has little effect on sheet hardness. The as-rolled hardness varied inversely with rolling temperature, however, annealing greatly reduced or eliminated this condition.

b. Room Temperature Tensile Properties

Initial tensile testing was limited to transverse tests annealed at 2300°F. and 2400°F. Additional samples were later submitted for both longitudinal and transverse testing for rolling variables of most interest. In general, the ultimate strength followed the relationship shown in Figure 10. The band in this figure includes TZM processed by all practices included in Phase I of this program. The tensile properties generally follow this hardness relationship. In the 2800°F. mold out annealed material, the ductility of the 10 minute

annealed product was poorer than that which received the one hour anneal. The remainder of properties are rather typical and can be more effectively discussed when results are complete.

c. Bend Properties

The poorest bend transition temperatures resulted on the 2800°F. mold out annealed material cross rolled to final gauge. Straight rolling this same material produced good bend transitions (0°F. to -50°F.). The straight roll practice, however, is not being considered based on previous work. In addition to the less isotropic properties which result, an orange peel surface condition will result during bending. This orange peel condition is considered detrimental to subsequent coating operations.

The extremely poor bend properties of the 96 per cent worked material also eliminate it from further consideration. In addition, the high lamination tendency of this material and material following the 2550°F. mold out annealing practice add to the undesirability of these practices. The area of interest is thus reduced to material annealed at 2700°F. (sheet numbers 2738 through 2746 and 2759, 2760 in Table V).

Bend transition tests were conducted on a universal test machine. Specimens 3/4" wide by 1-1/8" long were punched through an open die at a ram rate of 8" per minute using a 4T punch. Minimum bend

radius tests were run in the same manner at room temperature. The flange test consisted of bending small panels approximately 8" wide in a hand bend break at room temperature in the transverse direction to failure or 145° maximum. The bend radius was less than 1T. The two results recorded in Table V represent a bend on each side of the sheet. Lamination tendency tests were conducted on bend transition specimens which successfully formed. The samples were flattened on a press, rebent and flattened until failure occurred. A rating of 0 indicates failure the first flattening operation; 1 - failure on the rebend; 2 - failure on reflattening, etc. The initial bend temperature on these specimens varied considerably. An additional set of samples is being prepared and all bending will be at room temperature using a 4T punch. Bend transition was also determined on samples which were recrystallized at 2700°F.

Table VI summarizes the bend properties of the nine variables containing 90 per cent cold work following a 2700°F. anneal at .750" mold out (sheet 2738 through 2746). The 2300°F. final sheet anneal values were used for this comparison. With respect to final mold out anneal, the 2150°F. practice resulted in the best average bend properties. Although the 1400°F. final rolling practice resulted in the lowest average bend transition, the 1800°F. rolling practice produced

the best minimum bend radius and flangeability properties. Table V shows bend transition of recrystallized material to be in the 0°F.—75°F. range for all variables.

It will be noted in Table V that the sheet containing 80 per cent cold work exhibited good bend properties. The bend transition temperature following a 2300°F. anneal was 0°F. for cross rolled material and -25°F. for straight rolled. Bend radius was 0T and flangeability was good.

d. Selection of Phase III TZM Rolling Practice

Based on bend test evaluation, the first mold out annealing practice was established at 2700°F. Although material containing 80 per cent total cold work exhibited good bend properties, Table V indicates the room temperature strength to be 10,000 to 15,000 psi lower than the 90 per cent worked material. Comparison of bend properties does not justify this loss of strength resulting in the less cold worked material.

In reviewing Table VI, an improvement in bend properties resulted by lowering the final in-process annealing temperature and raising the final rolling temperature. Although evaluation of the sheet variables is not complete, the practice tentatively established for Phase III pilot sheet rolling is as follows:

(1) Ingot - 8" single melt practice

(2) Extrude to 4-1/4-4-1/2" diameter at 2100°F.

(3) Hot forge sheet bar to 1-1/2" x 4" x length

(4) Roll at 2200°F. to gauge required to produce 90 per cent work in final sheet (.750" for .060" sheet)

(5) Recrystallize at 2700°F.

(6) Roll at 2200°F.—65 per cent reduction (.260" for .060" sheet)

(7) Stress-relieve at 2150°F.

(8) Roll to final gauge at 1800°F.

(9) Stress-relieve at 2300°F.

4. Evaluation of InFab Rolled Sheet

a. Hardness and Recrystallization

Sheet samples from the InFab rolled .060" sheet were annealed over the temperature range of 2300°F. to 2700°F. The resulting hardnesses are presented in Figure 11. Note that as-rolled hardness increased with decreasing rolling temperature from 2600°F. to 2200°F. Rolling at 1800°F. and 2000°F. resulted in lower as-rolled hardness. Little hardness drop occurred from annealing for one hour at 2300°F. A sharp drop occurred from the 2400°F. anneal and 10 to 20 per cent recrystallization was noted in all samples. Approximately 90 per cent recrystallization was noted in all variables following the 2600°F. anneal except for the sheet rolled at 2600°F. Although not indicated by the hardness, the microstructure appeared to be approximately 70 per cent recrystallized.

b. Room Temperature Tensile Properties

Initial tensile tests were run on samples in the as-rolled surface condition. The results are shown in Table VII. Due to laminated product, no material was available for tensile testing T-16 sheet. Ultimate strength was in the range of 70,000 to 100,000 psi with no yield point and less than one per cent elongation. Micro examination of the sheet surface (Figure 12) revealed contamination ranging from a light typical appearing surface contamination condition on 1800°F. rolled material to a heavy duplex condition on the 2600°F. rolled sheet. Additional samples in the pickled condition have been submitted for tensile testing.

c. Bend Properties

Bend transition of pickled samples representing material rolled 2000°F. and 2200°F. was +25°F. Above 2200°F., the transition temperature increased approximately 25°F. with each 200°F. increase in rolling temperature. Minimum bend radius at room temperature was 0T on all but the 2600°F. rolled sheet annealed at 2400°F. (2T).

Flange test results transverse to the rolling direction and on pickled 8" panels are also included in Table VII. In the 2300°F. stress-relieved condition, sheet rolled at 1800°F.,2200°F. and 2400°F. bent 90° without failure. When

annealed at 2400°F., only the 2200°F. rolled material bent 90°.

In general, the bend properties of sheet rolled at these high temperatures is similar to material rolled at lower temperatures and recrystallized.

C. Summary

Ten sheets of Mo+0.5%Ti, 0.060 in. x 24 in. x 72 in. ~~have been~~ were produced, five sheets from each of two ingots. Tests from two sheets from one ingot show flatness to be within 1% ~~one per cent~~ and gauge within ± .002 in. Bend transition was in the range of 0°F. to -75°F. with a recrystallization temperature of 2250°F. Unusually high 2000°F. tensile property results are being checked.

Rolling of material for Phase II TZM was accomplished. Testing of the product is approximately 90% ~~per cent~~ complete. A tentative process for Phase III pilot rolling ~~has been~~ was selected.

IV Anticipated Progress Next Report Period (January 26, 1963 to April 25, 1963)

The remaining Mo+0.5%Ti extrusion billet will be hot forged and rolled to .020" sheet thus completing Phase III for this alloy.

Ingots for Phase III TZM will be melted, extruded and hot forged to sheet bar. Quantities of sheet will be rolled to each of the four required gauges and tested.

By W. A. McNeish

Approved By L. M. Bianchi

TABLE I

Mo+0.5%Ti Phase III Rolling Schedule
.060" x 24" x 72" Sheet

1. Apply hot forged sheet bar approximately 1-3/4" x 4" x 24"
2. Roll from 2200°F. furnace to .750" x 24" wide x length
3. Sandblast
4. Anneal 1 hour @ 2800°F., Hydrogen atmosphere
5. Sandblast, Ultrasonic, Trim, Grind
6. Roll from 2200°F. furnace to .260" x 24" wide x length
7. Hydride pickle
8. Anneal 1 hour @ 2150°F., Hydrogen atmosphere
9. Hydride pickle
10. Ultrasonic, Trim, Spot Grind
11. Roll from 1600°F. furnace to .064/.068" x 25" wide x length (Cross roll from previous rolling direction)
12. Trim all edges
13. Warm flatten (approx. 600°F.), Roller leveler
14. Hydride descale
15. Anneal 2150°F., Hydrogen atmosphere
16. Hydride descale
17. Grind
18. Pickle to gauge
19. Warm shear to 24" x 72" (≤ 500°F.)
20. Inspect and Test

TABLE II

Processing Sizes and Yields
of Phase III Mo+0.5%Ti, .060" Sheet

Sheet Bar Number	Sheet Bar Size	Weight	.750" Length	.260" Length	Rough Sheared Sheet Size	Sheet Weight	Sheet Bar - Sheet Yield
1126B1	1-7/8 x 4-1/8 x 29	75	11	26	25-1/2 x 78-1/4	48	64
1126B2	2 x 3-1/2 x 25	65	9-3/8	26	25-1/2 x 83-1/2	50	77
1126B3	1-5/8 x 4-1/4 x 25-1/4	69	9-1/8	25-3/4	25-1/4 x 83-3/8	52	75
1126B4	1-5/8 x 4-1/4 x 26-1/4	66	9-1/4	26-1/4	25-3/4 x 80-3/4	50	76
1126B5	1-3/4 x 4-1/2 x 24	70	10-1/2	25-3/4	25-1/4 x 79	50	72
		345				250	73
1127B1	1-7/8 x 4-1/8 x 26-1/2	71	10-1/8	26-1/4	25-3/4 x 79	48	68
1127B2	1-5/8 x 4-1/2 x 25-1/2	69	9-3/4	25-3/4	25-1/2 x 83-3/4	47	68
1127B3	1-5/8 x 4 x 28-1/4	67	9	25	24-3/8 x 82-3/4	41	61
1127B4	1-5/8 x 4-1/2 x 27	71	9-7/8	25-1/4	24-1/2 x 81	41	58
1127B5	1-3/4 x 4-1/4 x 26-3/4	70	10	25-1/2	24-3/4 x 82	45	64
		348				222	64

TABLE III

Gauge Survey of As-Rolled
Phase III Mo+0.5%Ti, .060" Sheet

Sheet Number	Sheet Location (Readings in Mils) 1	2	3	4	5	6	7	8	9	10	11	12	Range	Average
1126B1	62.0	64.0	63.0	64.5	64.0	64.0	67.0	62.0	62.5	62.5	63.0	64.0	62.0-67.0 (5.0)	63.5
1126B2	62.5	64.0	64.0	64.0	63.0	64.0	66.0	62.5	63.0	62.5	63.0	64.0	62.5-66.0 (3.5)	63.5
1126B3	65.5	68.0	68.0	68.0	65.0	67.5	67.5	65.5	68.0	67.0	67.0	66.0	65.0-68.0 (3.0)	67.0
1126B4	65.5	66.0	66.0	66.5	65.0	65.5	66.5	66.0	67.0	66.0	67.0	63.5	63.5-67.0 (3.5)	66.0
1126B5	68.0	67.0	67.0	63.0	64.0	69.0	65.0	66.0	66.0	65.0	64.0	64.0	64.0-69.0 (5.0)	66.0
1127B1	62.0	64.0	64.0	64.0	64.0	65.0	64.0	62.0	64.0	62.0	62.0	62.0	62.0-65.0 (3.0)	63.5
1127B2	62.0	63.5	64.0	64.0	66.0	63.5	68.0	62.0	64.0	64.0	64.0	66.0	62.0-68.0 (6.0)	64.0
1127B3	64.0	66.5	67.0	68.0	68.0	66.5	67.5	65.0	65.5	67.0	67.0	66.0	64.0-68.0 (4.0)	66.5
1127B4	64.0	65.0	63.5	65.0	64.0	66.0	65.5	64.0	65.0	64.0	64.5	64.0	63.5-66.0 (2.5)	64.5
1127B5	63.0	64.0	64.0	64.0	66.0	64.0	66.5	62.0	63.0	64.0	63.0	63.0	62.0-66.5 (4.5)	64.0

1	2	3	4	5
6				7
8	9	10	11	12

TABLE IV

Mold Out Hardness of
InFab Rolled TZM

	T-46	T-47	T-48	T-49	T-50
Rolling Temp.	1800°F.	2000°F.	2200°F.	2400°F.	2600°F.
As-Rolled .750"	304	297	330	309	268
Annealed .750" (2900°F.-10 min)	228	203	245	222	238
As-Rolled .260"	322	319	309	309	309
Annealed .260" (2350°F.-1 hour)	302	289	299	285	302

TABLE V

TZM Phase II .060" Sheet Data

Sheet Bar Number:		1097B3			1097B5			1097A2			1097B4			1096A2		1096A1		1096A1	
Sheet Number:		2735	2736	2737	2738	2739	2740	2741	2742	2743	2744	2745	2746	2759	2760	2761	2762	2763	2764
1 Mold Cut Anneal:		-1 hour @ 2550°F. (.750")			-1 hour @ 2700°F. (.750")			-1 hour @ 2700°F. (.750")			-1 hour @ 2700°F. (.750")			2700°F. (.325")		2700°F. (1.100")		1 hour @ 2450°F. (.750")	
2 Mold Cut Anneal:		2150	2300	2450	-1 hour @ 2150°F. (.260")			-1 hour @ 2300°F. (.260")			-1 hour @ 2450°F. (.260")			2300°F. (.145")		2300°F. (.270")		2300°F. (.225")	
Final Roll Temp. & Dir.:		1600°F. Cross Roll			1400/CR	1600/CR	1800/CR	1400/CR	1600/CR	1800/CR	1400/CR	1600/CR	1800/CR	1600/CR	1600/ST	1600/CR	1600/ST	1600/CR	1600/ST
Property	**Anneal**																		
Ultimate Strength (Transv.)	2200°F.	--	--	139.9	142.7	--	141.1	139.0	147.4	150.3	144.8	143.3	142.7	135.3	125.2	154.9	--	--	--
	2300°F.	145.1	152.9	144.6	141.9	143.1	134.9	153.2	146.6	147.4	143.1	140.8	141.7	132.6	130.5	151.6	138.4	162.0	--
	2300°F.	151.3	148.7	144.8	--	145.3	--	152.4	141.8	149.9	--	143.4	143.0	--	130.1	--	--	--	--
	2400°F.	143.6	147.8	142.8	139.2	135.1	--	148.4	142.3	141.5	138.9	135.7	135.8	132.4	126.4	145.6	149.2	158.2	157.0
Yield Strength (Transv.)	2200°F.	--	--	132.6	131.4	--	129.1	122.7	139.3	141.5	133.2	134.2	131.8	120.9	116.7	142.4	--	--	--
	2300°F.	135.2	137.5	131.8	130.1	132.9	126.9	142.1	137.7	139.1	128.5	130.4	132.5	118.2	119.4	136.6	131.2	147.2	--
	2300°F.	140.1	136.8	131.3	--	134.4	--	144.0	135.3	141.3	130.0	133.6	132.8	--	119.2	--	--	--	--
	2400°F.	133.1	135.2	131.0	129.8	124.1	--	141.4	135.4	136.7	128.4	127.6	130.9	118.0	116.2	134.1	140.5	143.5	148.8
% Elong. (Transv.)	2200°F.	--	--	7.4	7.6	--	7.6	16.6	8.6	7.4	8.0	3.7	7.6	14.0	10.3	5.2	--	--	--
	2300°F.	1.8	7.6	11.8	13.4	9.0	11.5	10.3	7.8	5.8	9.8	9.2	10.2	12.4	13.5	12.5	11.9	5.0	--
	2300°F.	9.3	4.4	11.5	--	11.3	--	10.3	5.1	8.4	1.0	8.6	7.8	--	16.0	--	--	--	--
	2400°F.	10.1	11.3	14.7	11.4	13.5	--	9.0	10.9	3.7	5.1	10.2	9.7	16.0	15.4	14.2	10.9	7.5	3.9
Ultimate Strength (Longit.)	2200°F.	144.7	139.9	135.2	133.4	130.7	132.3	142.2	138.2	140.4	138.5	135.5	135.7	131.0	127.4	145.0	150.7	--	--
	2300°F.	143.8	141.8	133.6	124.7	129.3	129.4	138.5	136.3	136.1	--	133.4	131.4	--	125.7	146.4	142.3	--	--
	2400°F.	131.8	129.9	--	128.9	--	--	111.1	127.1	125.7	123.8	--	121.0	--	126.3	132.5	--	--	--
Yield Strength (Longit.)	2200°F.	132.7	126.9	123.0	119.1	116.8	120.8	127.4	124.6	123.6	124.3	121.7	124.3	116.4	114.9	129.9	135.2	--	--
	2300°F.	133.3	130.2	122.5	112.3	117.1	119.6	123.8	122.3	123.0	--	120.7	119.5	--	113.7	131.0	127.7	--	--
	2400°F.	121.9	118.8	--	114.5	--	--	98.4	113.0	111.5	112.3	--	109.9	--	114.0	120.9	--	--	--
% Elong. (Longit.)	2200°F.	11.1	12.1	13.8	7.0	15.3	13.8	15.4	10.1	16.3	12.0	18.0	8.9	15.7	11.8	12.0	14.4	--	--
	2300°F.	12.2	10.5	12.4	14.6	13.9	17.7	18.9	13.2	14.0	--	11.5	17.7	--	10.0	13.3	13.9	--	--
	2400°F.	13.0	13.8	--	20.4	--	--	16.2	19.2	15.7	12.2	--	19.1	--	16.3	15.3	--	--	--
DPH (10 kg load)	As-Roll	348	342	348	335	327	338	355	330	350	336	330	342	317	304	357	365	390	401
	2200°F.	345	330	333	303	319	311	321	322	312	304	327	320	294	283	336	325	366	351
	2300°F.	342	336	325	317	306	311	319	322	316	317	327	314	297	292	319	335	357	357
	2400°F.	333	314	314	306	304	300	311	306	299	302	312	303	281	287	304	316	347	345
	2500°F.	297	279	306	244	235	238	261	270	251	248	268	256	254	272	253	243	281	327
	2600°F.	218	218	219	212	213	203	210	218	214	219	219	210	206	206	222	220	239	247
	2700°F.		203		200			205				211		199			208		
% Recrystallization																			
	2400°F.	Tr	Tr	Tr	--	Tr	--	--	Tr	--	--	Tr	--	Tr	Tr	Tr	5	Tr	5
	2500°F.	10	25	15	--	40	--	--	30	--	--	20	--	30	25	20	30	25	10
	2600°F.	70	60	60	--	50	--	--	50	--	--	50	--	60	60	70	75	50	40
4T Bend Transition (Transv.) °F.	2300	0	0	-25	-50	-50	-50	-25	-25	0	0	+25	+25	0	-25	0	0	+50	--
	2400	+75	0	-25	+75	0	-25	-25	0	-50	+75	0	+25	0	+50	0	-50	+50	+125
	2700	0	0	+25	+75	+25	+25	+25	+75	0	+50	+50	+75	+75	+125	+75	--	--	--
4T Bend Transition (Longit.) °F.	2700	0	0	+25	+50	+25	0	+75	+25	0	+25	+25	+25	+75	+50	+75	+25	--	--
Min. Bend Radius (Transv.)	2300	0T	0T	0T	0T	1T	0T	2T	0T	0T	2T	0T	0T	0T	0T	1T	2T	2T	4T
	2400	0T	0T	1T	0T	0T	0T	0T	1T	0T	0T	0T	0T	0T	0T	0T	0T	1T	4T
	2700	0T	0T	1T	0T	0T	0T	1T	0T	0T	1T	0T	0T	1T	--	0T	--	--	--
Min. Bend Radius (Longit.)	2700	0T	0T	0T	0T	0T	1T	0T	0T	0T	0T	0T	0T	0T	0T	0T	1T	--	--
Fiesse ° (Transv.)	2300	105-70	90-95	115-105	55-95	105-105	115-125	95-95	85-75	105-95	80-85	100-80	90-95	135-95	125-110	70-90	100-90	80-20	95-75
	2400	105-80	100-90	110-135	65-40	95-115	105-100	135-130	80-105	95-100	30-15	90-75	95-110	145-130	145-100	105-130	25-30	75-100	70-30
Back Bend	2300°F.	0	1	2	1	2	2	0	2	0	0	1	1	2	2	0	2	1	--
	2400°F.	1	2	0	2	0	0	0	0	0	0	0	0	0	2	0	0	0	--

TABLE V

TZM Phase II .060" Sheet Data

Sheet Bar No.:		1096B4			1096A5			1096A4			1096A3		
Sheet No.:		2747	2748	2749	2750	2751	2752	2753	2754	2755	2756	2757	2758
Anneal @ .750"		1 hour @ 2800°F.			1 hour @ 2800°F.			10 minutes @ 2800°F.			10 minutes @ 2800°F.		
Anneal @ .260"		2150	2300	2450	2150	2300	2450	2150	2300	2450	2150	2300	2450
Roll Temp. & Dir.:		1600/CR	1600/CR	1600/CR	1600/ST	1600/ST	1600/ST	1600/CR	1600/CR	1600/CR	1600/ST	1600/ST	1600/ST
Property	**Condition**												
U.T.S.	2300°F.	135.7	155.9	137.5	143.8	148.4	144.6	146.7	146.4	--	152.3	142.8	151.6
(Transv.)	2400°F.	121.9	130.5	127.8	140.0	141.3	138.1	146.4	142.8	143.0	148.6	149.1	147.2
Y.S.	2300°F.	125.6	146.2	123.4	127.8	136.1	137.3	136.8	134.4	--	140.4	136.9	145.8
(Transv.)	2400°F.	--	122.3	118.5	126.3	130.6	130.6	135.7	131.7	133.5	138.4	139.6	139.1
% Elong.	2300°F.	11.9	9.8	12.0	7.2	10.1	11.0	1.6	9.0	--	9.7	0.7	9.3
(Transv.)	2400°F.	1.2	15.5	14.7	8.6	11.0	12.6	9.6	13.3	12.3	9.0	8.6	8.6
DPH	As-Rolled	314	341	339	339	342	330	354	345	359	348	354	357
10 kg Load	2200°F.	312	318	314	314	325	309	333	327	344	327	336	333
	2300°F.	309	308	302	306	306	298	325	314	312	327	317	333
	2400°F.	299	285	299	294	283	293	304	304	323	319	322	314
	2500°F.	256	228	238	236	225	227	266	268	281	279	272	272
	2600°F.	199	206	197	202	203	212	206	218	215	207	206	207
% Recrystallization													
	2300°F.	0	Tr	0	0	0	Tr	0	0	0	0	0	0
	2400°F.	5	10	10	5	10	10	Tr	Tr	Tr	5	10	5
	2500°F.	40	40	40	50	50	60	30	25	15	20	20	20
	2600°F.	90	90	90	90	85	100	70	60	65	85	80	80
4T Bend	2300°F.	+50	+100	+75	-25	-50	-50	+50	-25	+25	0	0	+50
Transition °F.	2400°F.	+100	+25	+75	0	-25	0	+125	+50	+100	0	0	+25
Flange	2300°F.	60-85	115-120	120-100	100-100	90-85	65-85	95-95	80-10	105-105	110-90	15-55	85-85
	2400°F.	120-130	110-125	115-70	105-95	90-105	115-105	95-75	75-85	70-35	115-95	25-115	100-100
Minimum Bend Radius	2300°F.	0T	0T	2T	0T	0T	2T	0T	1T	0T	2T	4T	2T
	2400°F.	0T	0T	2T	0T	1T	0T	4T	0T	0T	0T	0T	0T

TABLE VI

Effect of In-Process Anneal
and Final Rolling Temperature
on Bend Properties of .060" TZM Sheet

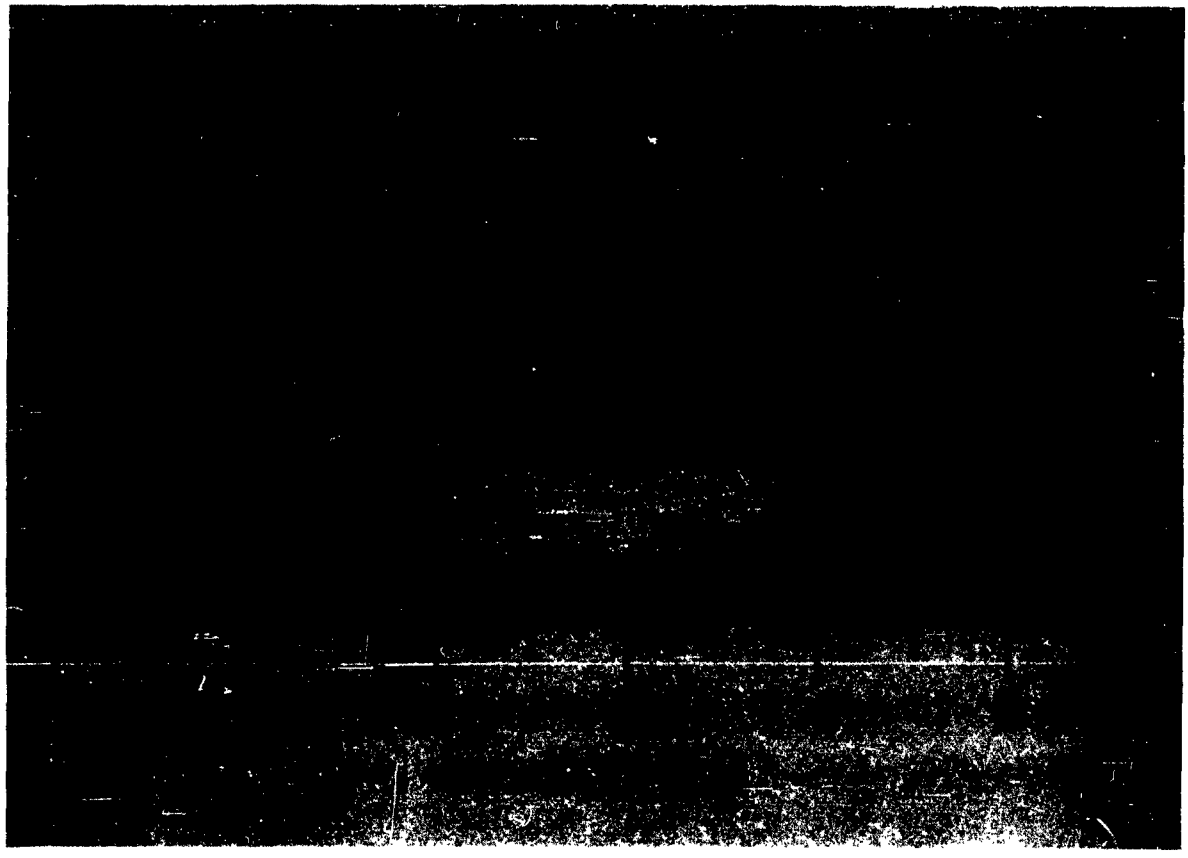
	Mold Out Anneal	1400°F.	1600°F.	1800°F.	Average
Bend Transition	2150°F.	-50°F.	-50°F.	-50°F.	-50°F.
	2300°F.	-25°F.	+25°F.	0°F.	0°F.
	2450°F.	0°F.	+25°F.	+25°F.	+17°F.
Average		-25°F.	0°F.	- 8°F.	
Minimum Bend Radius	2150°F.	0T	1T	0T	1/3T
	2300°F.	2T	0T	0T	2/3T
	2450°F.	2T	0T	0T	2/3T
Average		1-1/3T	1/3T	0T	
Flange Test	2150°F.	75°F.	105°F.	120°F.	100°F.
	2300°F.	95°F.	80°F.	100°F.	92°F.
	2450°F.	87°F.	90°F.	92°F.	90°F.
Average		86°F.	92°F.	104°F.	

NOTE: All samples cold rolled 90% and annealed one hour @ 2300°F.

TABLE VII

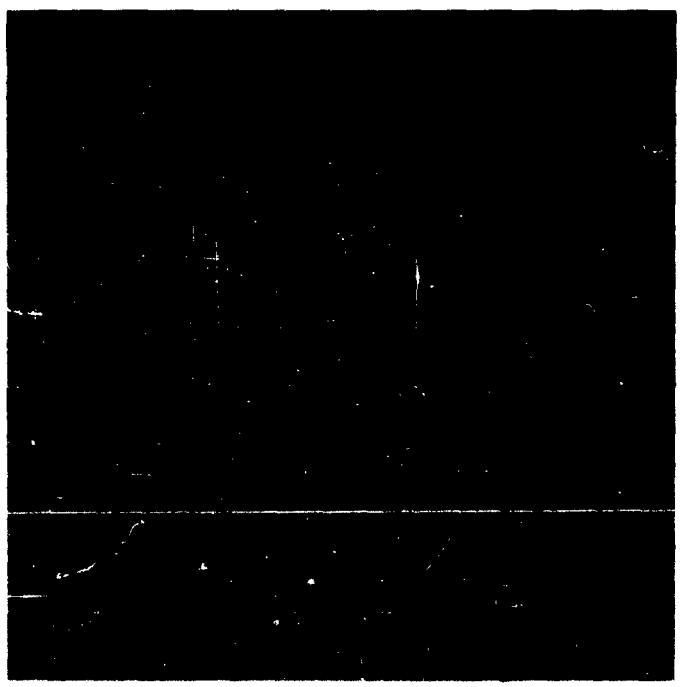
Properties of InFab Rolled TZM Sheet

Sheet Number		T-46	T-47	T-48	T-49	T-50
Rolling Temp.		1800°F.	2000°F.	2200°F.	2400°F	2600°F.
	Condition					
UTS (X1000)	2300°F. SR (As-Rolled Surface)	--	90.7	97.8	90.3	72.1
	2400°F. SR (As-Rolled Surface)	--	99.4	80.1	81.2	81.2
Elongation (%)		--	.7	.6	.5	.2
		--	.2	.8	.6	.4
Bend Transition (°F.)						
	2300°F. SR (Pkld.)	--	+25°	+25°	+50°	+75°
	2400°F. SR (Pkld.)	--	+25°	+25°	+50°	+100°
Minimum Bend Radius						
	2300°F. SR (Pkld.)	--	OT	OT	OT	OT
	2400°F. SR (Pkld.)	--	OT	OT	OT	2T
Flange Test	2300°F. SR (Pkld.)	90°	40°	90°	90°	70°
	2400°F. SR (Pkld.)	--	10°	90°	60°	30°



R12628

FIGURE 1 - MACROSTRUCTURE OF PHASE II
TZM HOT FORGED SHEET BAR



R12860 200X

FIGURE 2 - MICROSTRUCTURE AND SURFACE CONDITION OF TZM SHEET BAR KDTZM 1096B

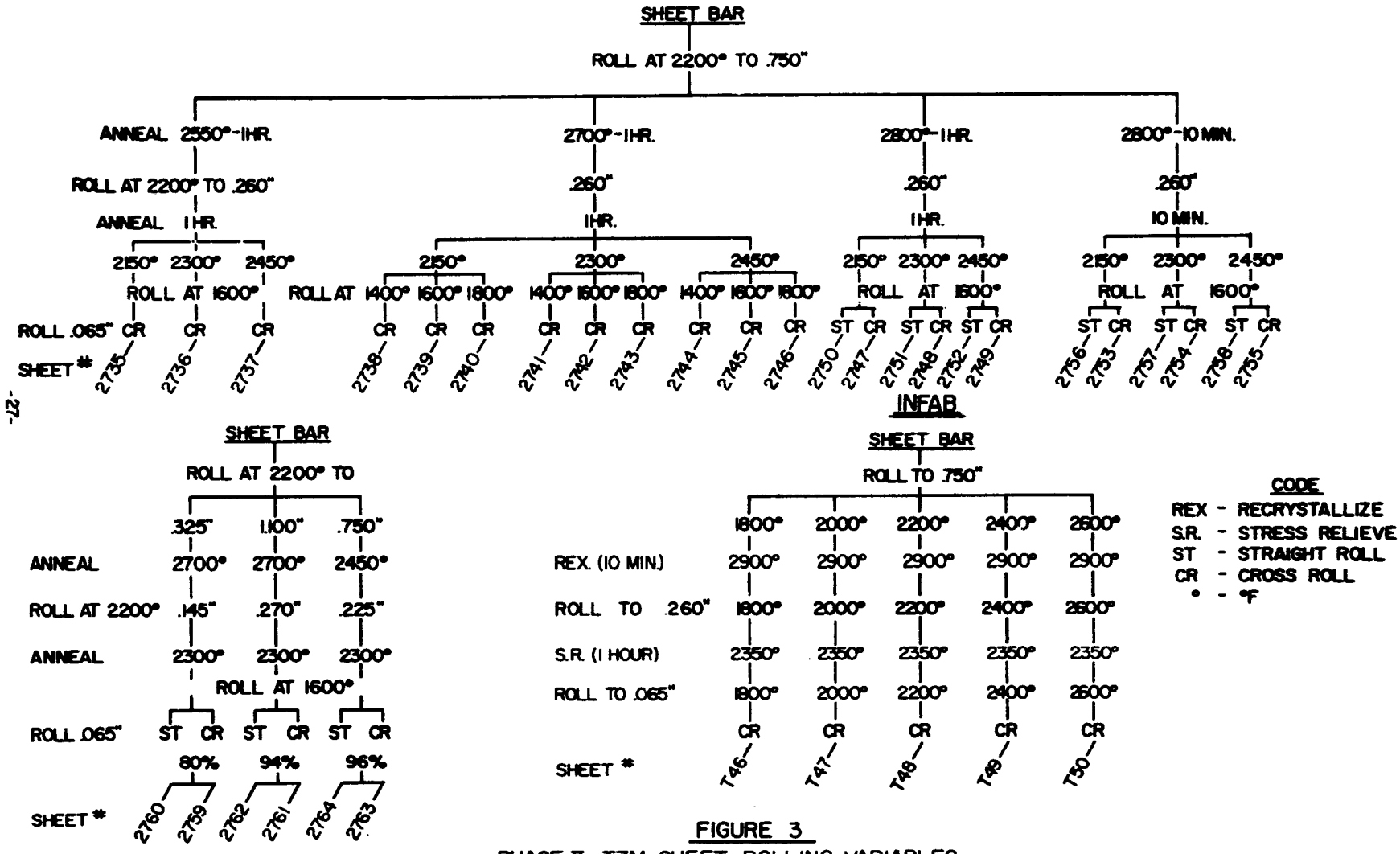


FIGURE 3

PHASE II TZM SHEET ROLLING VARIABLES

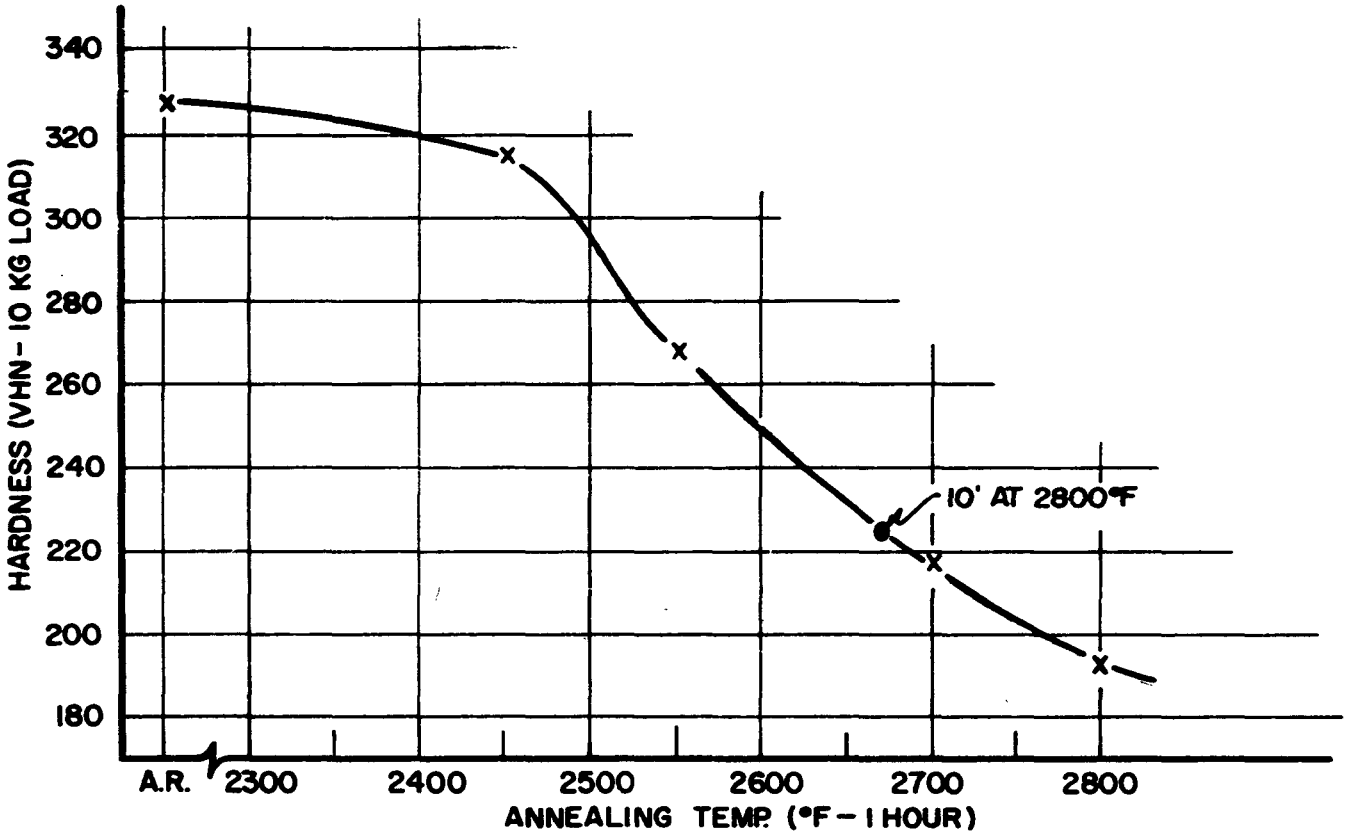
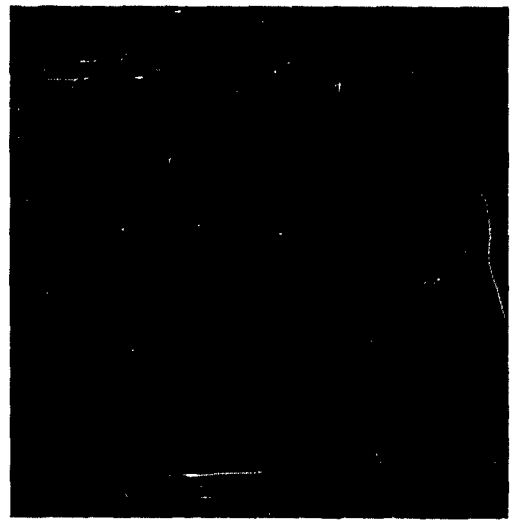


FIGURE 4
HARDNESS OF ANNEALED .750" MOLD OUT
PHASE II TZM

R12861 500X

A. As-Forged Sheet Bar



R12698 1000X

B. As-Rolled at 2400°F. to .750"

R12695 200X

C. .750" Mold Out Annealed at 2900°F.

FIGURE 5 - CARBIDE CONDITION IN SHEET BAR AND MOLD OUT - 1096B5

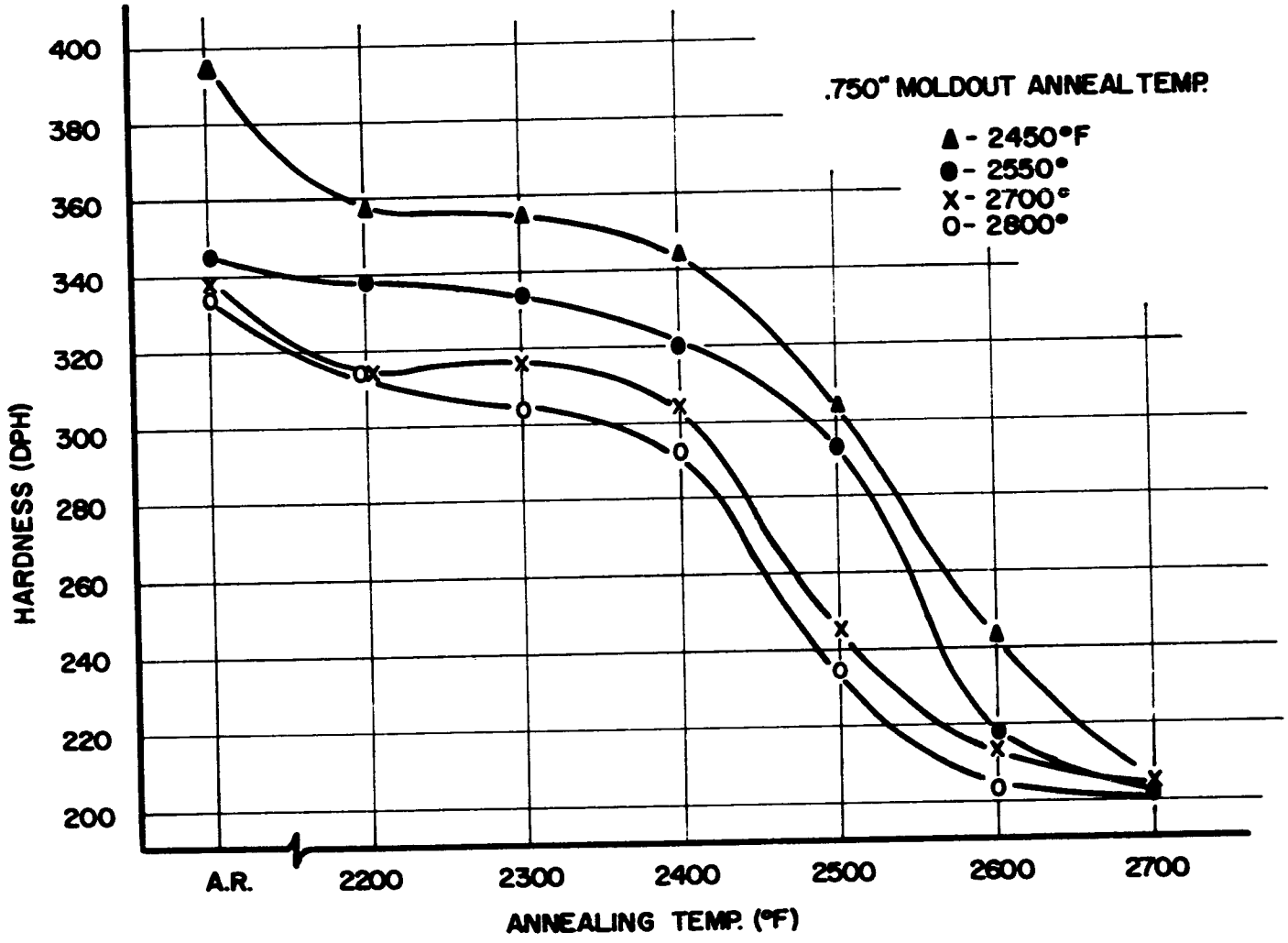


FIGURE 6

EFFECT OF .750" MOLDOUT ANNEALING TEMPERATURE
ON HARDNESS OF .060" TZM SHEET

RTA-0301

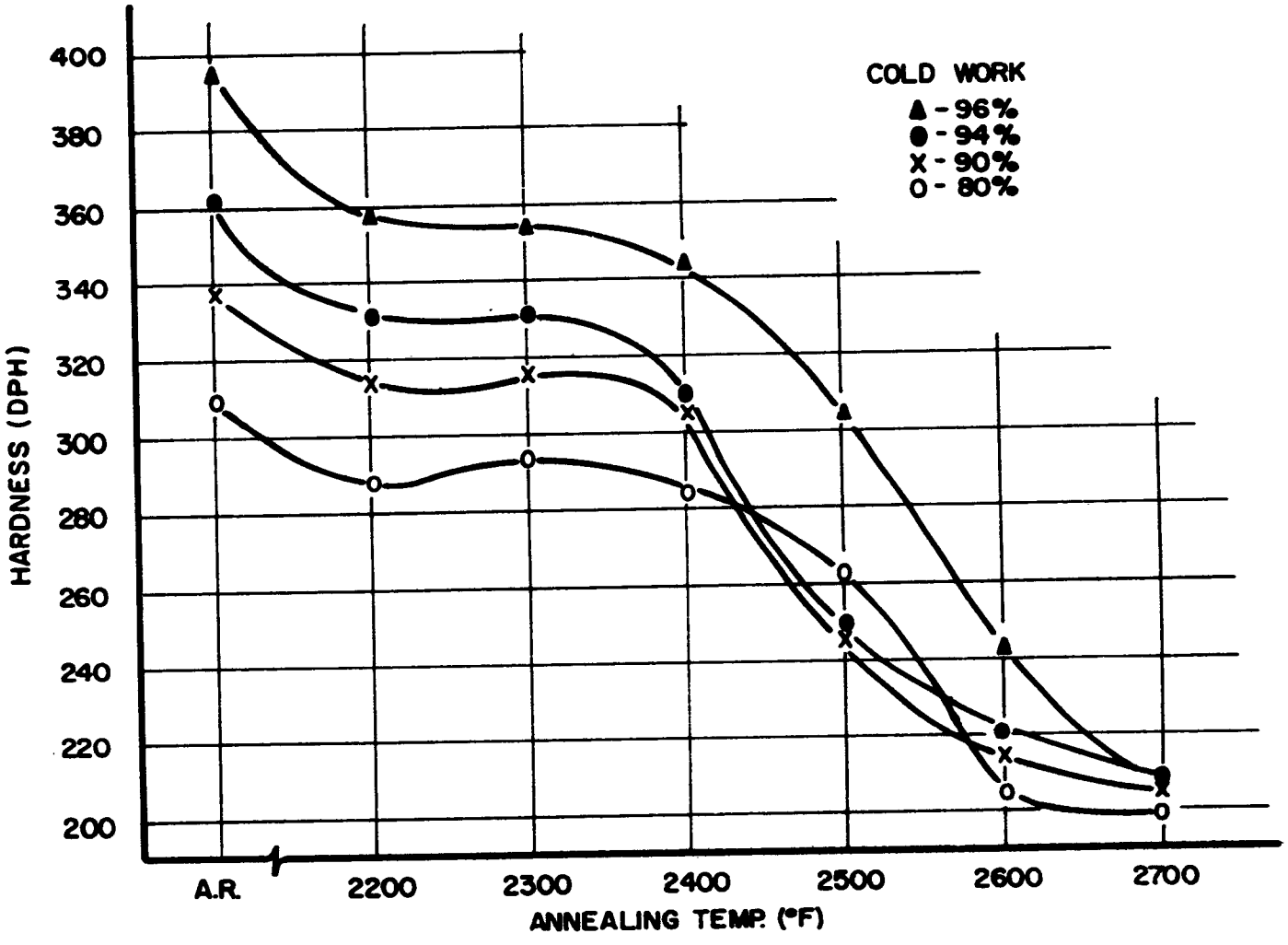


FIGURE 7

EFFECT OF PERCENT COLD WORK ON .060" TZM SHEET

RTA-0302

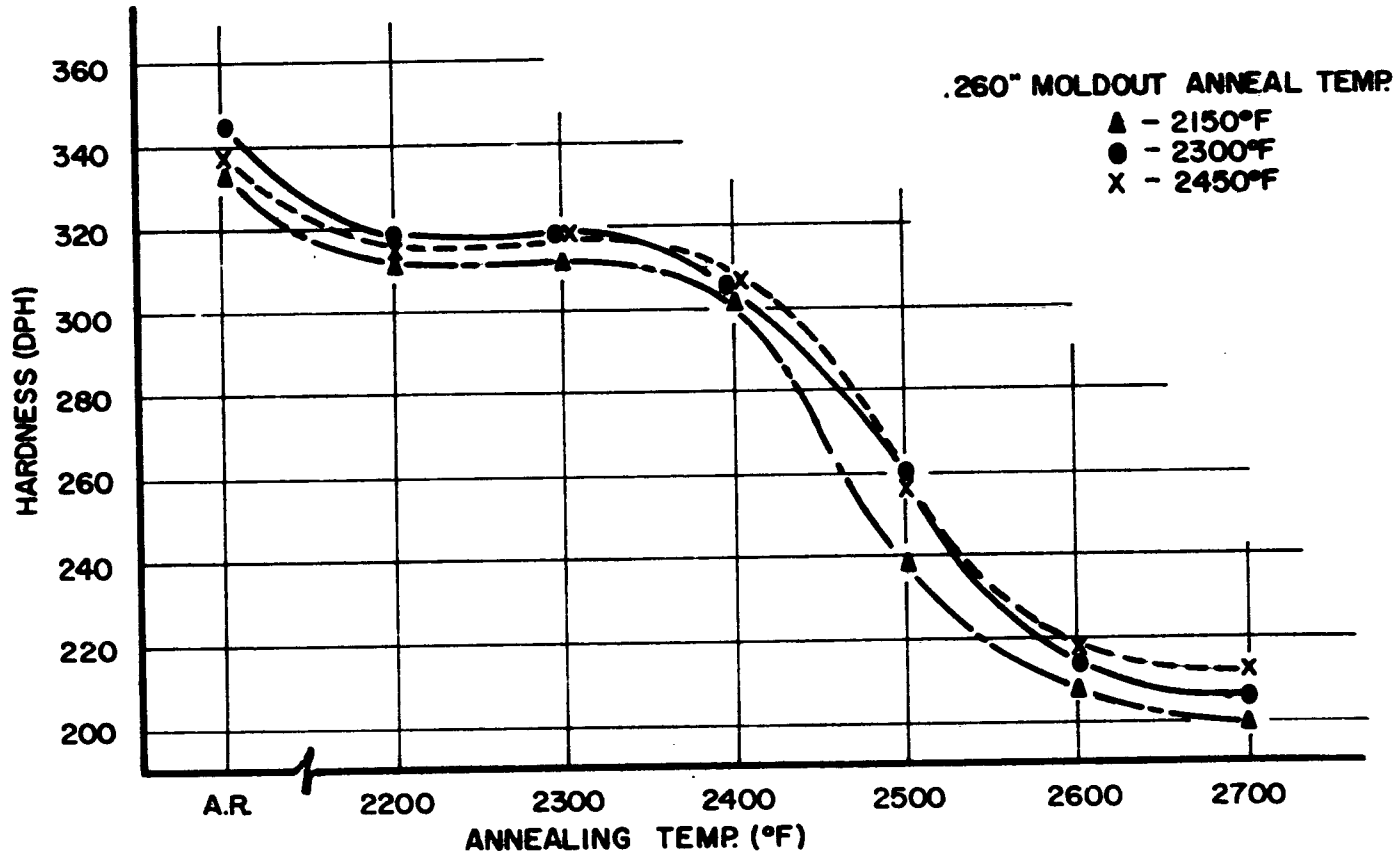


FIGURE 8

EFFECT OF .260" MOLDOUT ANNEALING TEMPERATURE
ON HARDNESS OF .060" TZM SHEET

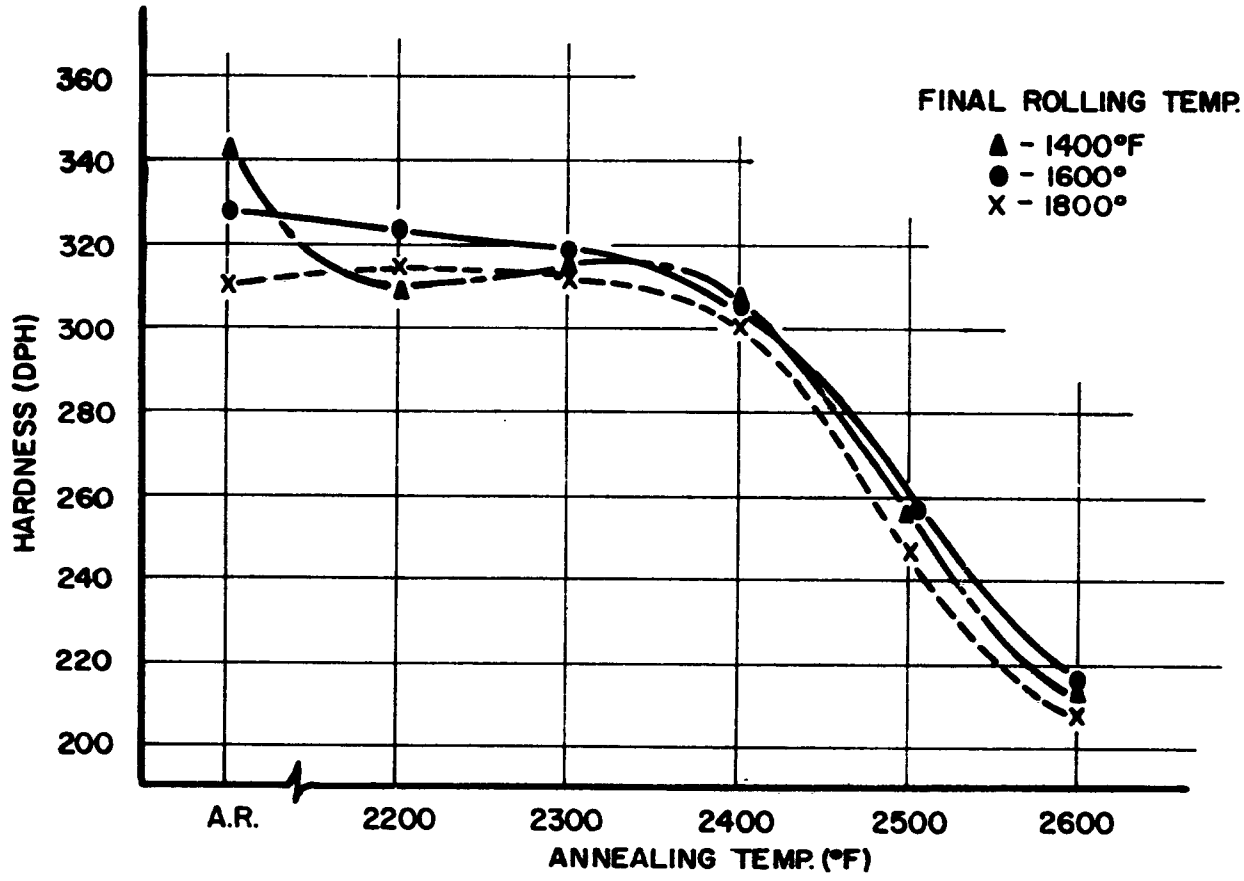


FIGURE 9

EFFECT OF FINAL ROLLING TEMPERATURE
ON HARDNESS OF .060" TZM SHEET

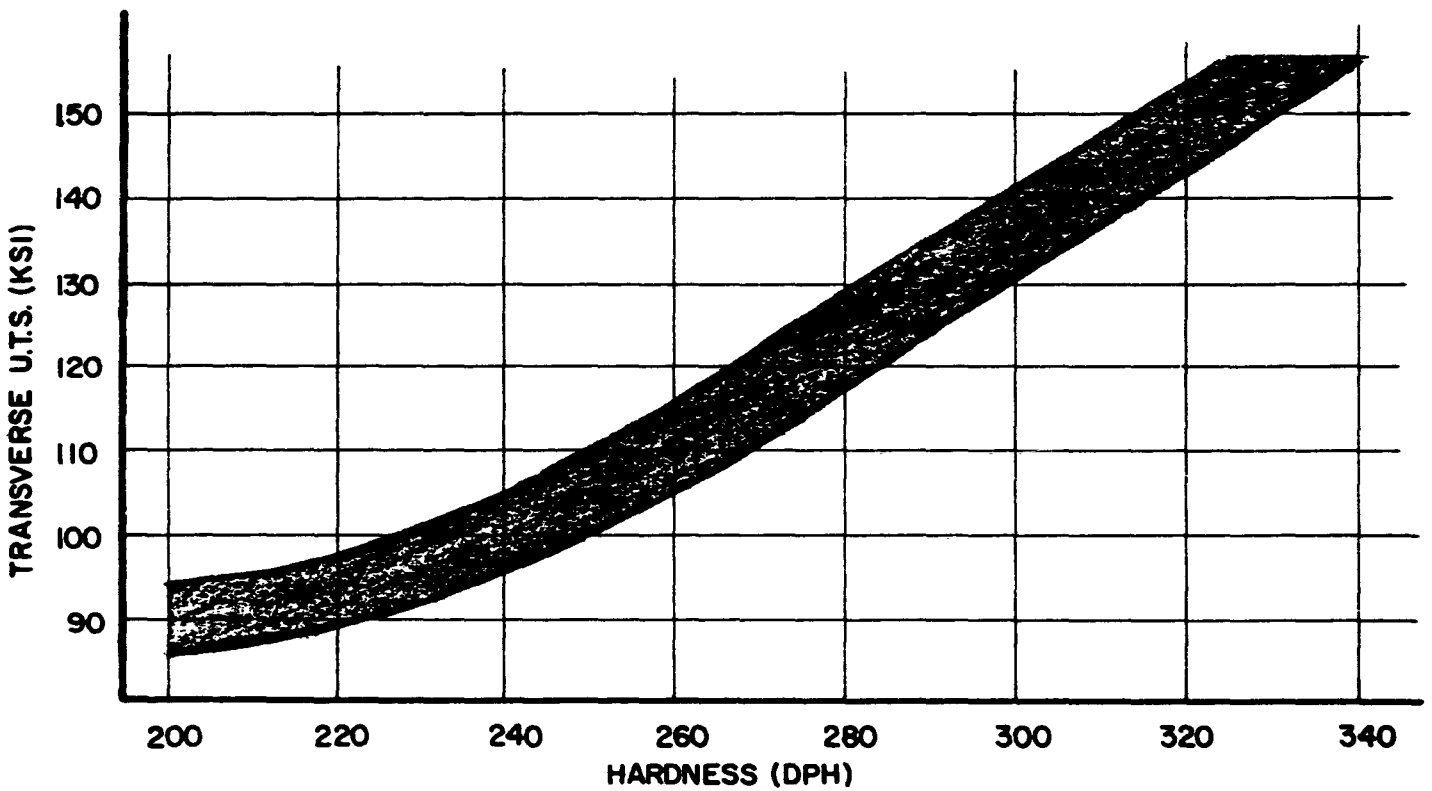


FIGURE 10
TRANSVERSE ULTIMATE STRENGTH VS HARDNESS
ON .060" TZM SHEET

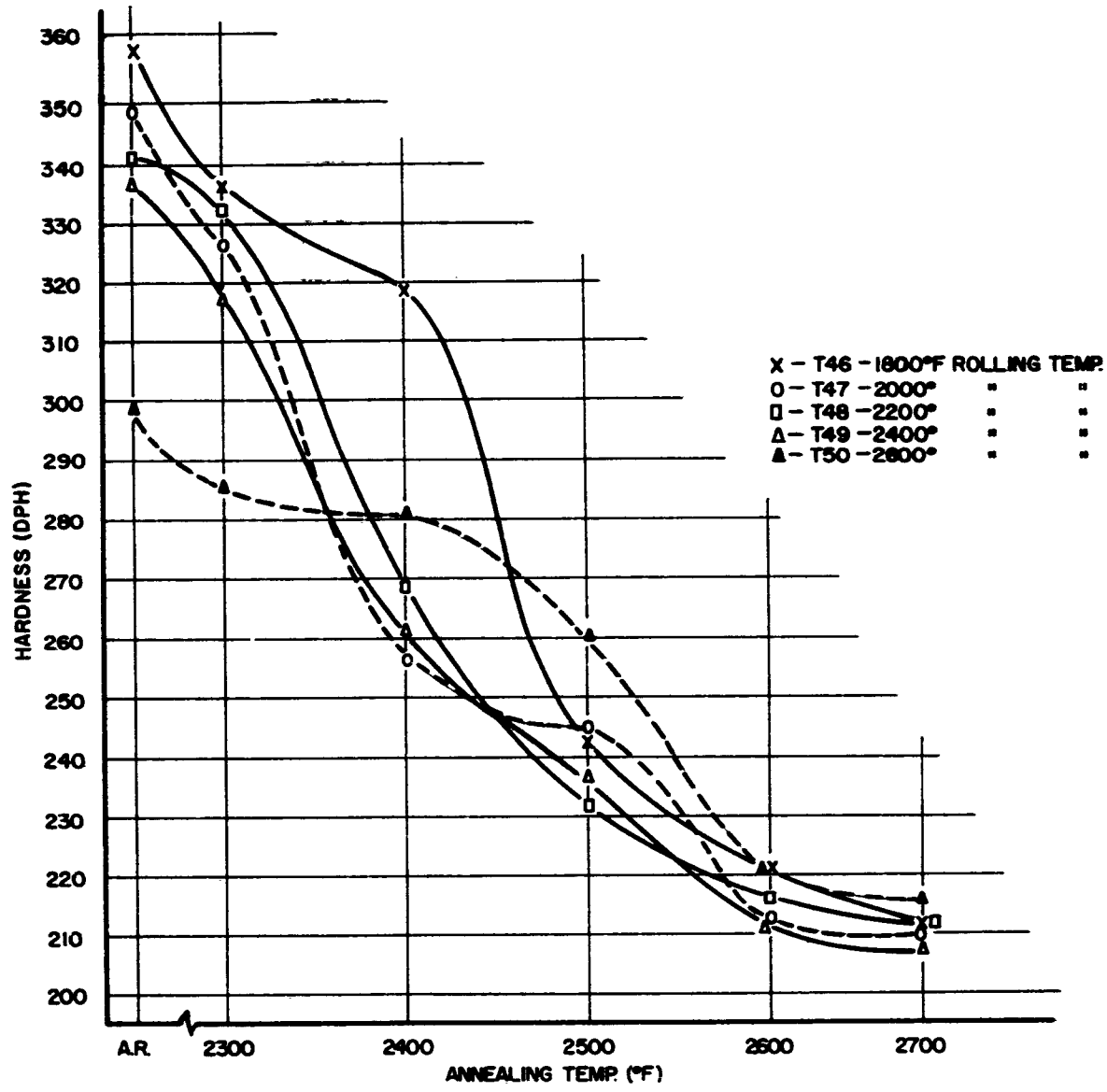
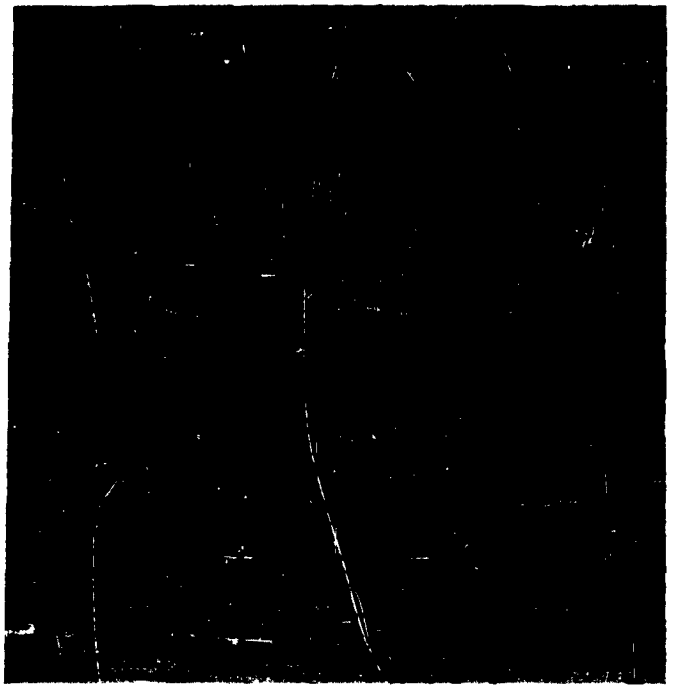


FIGURE 11

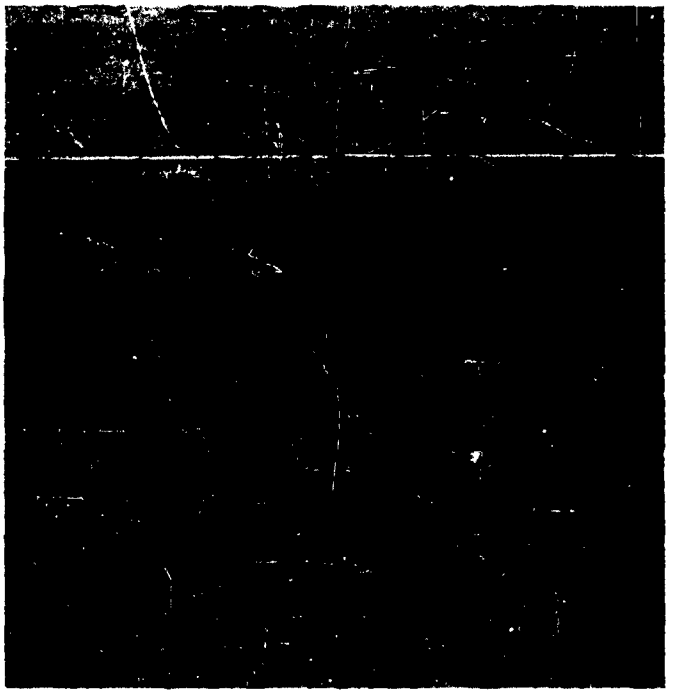
HARDNESS VS. ANNEALING TEMPERATURE FOR .060" INFAB ROLLED TZM SHEET

RTA-0306



R12851 200X

A. 1800°F. Rolled Sheet



R12854 200X

B. 2600°F. Rolled Sheet

FIGURE 12 - SURFACE CONDITION OF INFAB ROLLED .060" SHEET

SHEET TEST REPORT

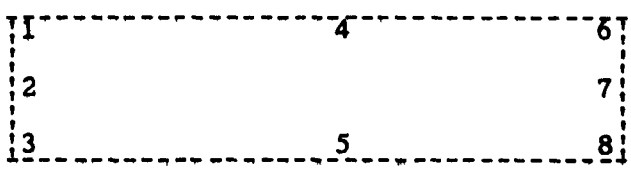
Alloy: Mo+0.5%Ti
Producer: Universal-Cyclops Steel Corp.
Contract Number: NOas 59-6142-c
Condition: HRolled, Stress Rlv'd., Pkld.
Month and Year Produced: 11/62

Sheet Serial No.: 4
Lot No.: T-2905
Heat No.: KD 1126B
Position in Ingot: Bottom
Sheet Size (Nom.)
Gauge: .060"
Length: 72"
Width: 24"

Visual Inspection:

Dimensional:

Length: 72-1/8"
Width: 24-1/16"
Camber: --
Thickness: 1 .061" 2 .061" 3 .061"
4 .062" 5 .062" 6 .061"
7 .062" 8 .059"



Flatness: 1%
Oil Can: --

Sonic: --

Chemistry of Sheet:

Alloy: 1 Ti .51% 2 3 4
Impurity: 1 Fe < .0015% 2 Si < .0035% 3 4
Interstitial: O 6 PPM N 2 PPM C .025% H 4.4 PPM

Tensile Properties	Ultimate, psi x 10^3	Yield, psi x 10^3	Elong., % in. 2"
Room Temperature:			
End A, Transverse	139.9	131.8	10.6
End A, Longitudinal	129.4	112.5	14.8
End B, Transverse	136.5	129.5	9.8
End B, Longitudinal	126.9	113.6	15.4
Room Temperature, Notched			
End A, Longitudinal	121.0		
End B, Longitudinal	130.5		
2000°F.			
End A, Transverse			
End A, Transverse	86.2	78.9	7.7
End A, Transverse	87.0	79.5	7.1
End B, Transverse	83.3	76.0	5.3
End B, Transverse	87.2	83.6	4.5
End B, Transverse	86.9	82.0	8.3

Bend Transition Temperature:

End A, Transverse -50 °F.

End B, Transverse 0 °F.

End B, Longitudinal -75 °F.

Metallographic Results:

Structure: Cold Worked

Average Grain Diameter: _____

Inclusions: _____

Hardness Results:

Readings, DPH 279 276 272 274

Average, DPH 275

50% Recrystallization Temperature (1 hour):

End A: 2250 °F.

End B: 2250 °F.

SHEET TEST REPORT

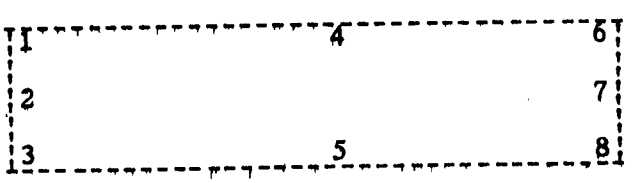
Alloy: Mo+0.5%Ti
Producer: Universal-Cyclops Steel Corp.
Contract Number: NOas 59-6142-c
Condition: HRolled, Stress Rlv'd., Pkld.
Month and Year Produced: 11/62

Sheet Serial No.: 5
Lot No.: T-2905
Heat No.: KD 1126B
Position in Ingot: Bottom
Sheet Size (Nom.)
Gauge: .060"
Length: 24"
Width: 72"

Visual Inspection:

Dimensional:

Length: 72-1/16"
Width: 24"
Camber: --
Thickness: 1 .060" 2 .061" 3 .059"
4 .061" 5 .059" 6 .061"
7 .058" 8 .059"



Flatness: 1%
Oil Can: --

Sonic: --

Chemistry of Sheet:

Alloy: 1 Ti .51% 2 ____ 3 ____ 4 ____
Impurity: 1 Fe < .0015% 2 Si < .0035% 3 ____ 4 ____
Interstitial: O 7 PPM N 2 PPM C .028% H 4.4 PPM

Tensile Properties	Ultimate, psi x 10^3	Yield, psi x 10^3	Elong.,% in. 2"
Room Temperature:			
End A, Transverse	138.2	130.9	8.2
End A, Longitudinal	125.5	112.4	15.0
End B, Transverse	137.8	127.6	5.5
End B, Longitudinal	126.7	112.6	17.8
Room Temperature, Notched:			
End A, Longitudinal	126.5		
End B, Longitudinal	125.9		
2000°F.			
End A, Transverse	91.1	84.6	7.8
End A, Transverse	93.2	85.6	5.8
End A, Transverse	112.0	102.7	8.5
End B, Transverse	112.5	104.0	5.9
End B, Transverse			
End B, Transverse			

Bend Transition Temperature:

End A, Transverse -25 °F.

End B, Transverse 0 °F.

End B, Longitudinal -50 °F.

Metallographic Results:

Structure: Cold Worked

Average Grain Diameter:

Inclusions:

Hardness Results:

Readings, DPH 281 283 274 268

Average, DPH 276

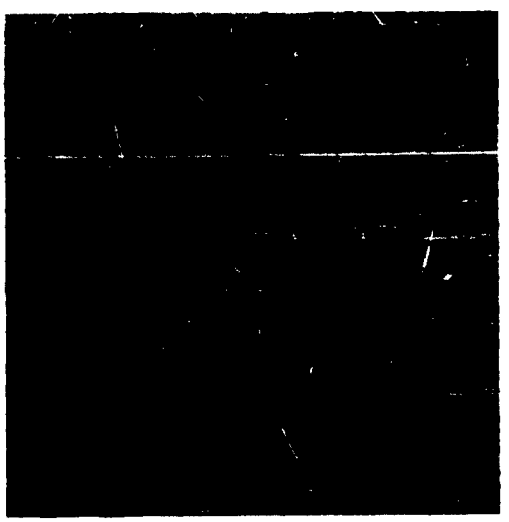
50% Recrystallization Temperature (1 hour):

End A: 2250 °F.

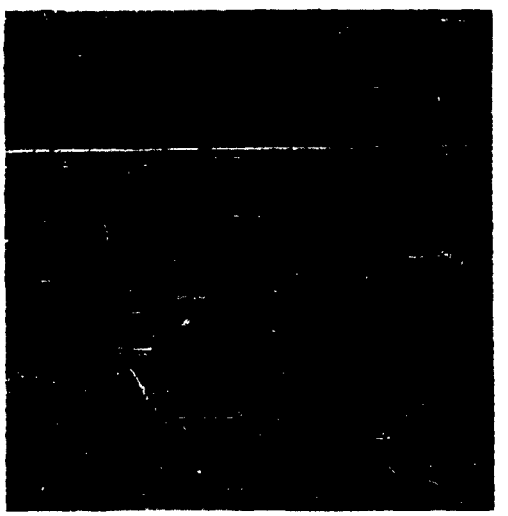
End B: 2250 °F.

R12727 4AH 200X

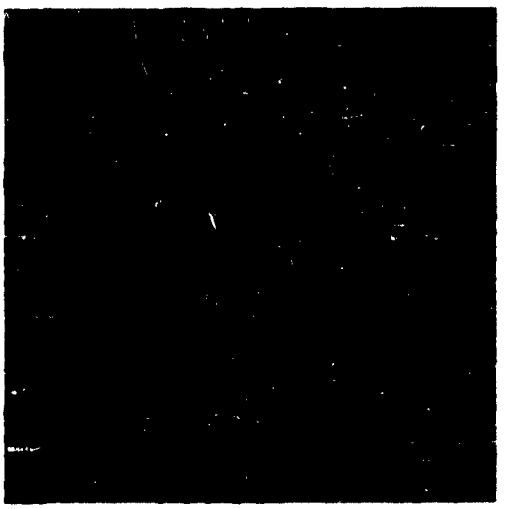
R12728 4BH 200X



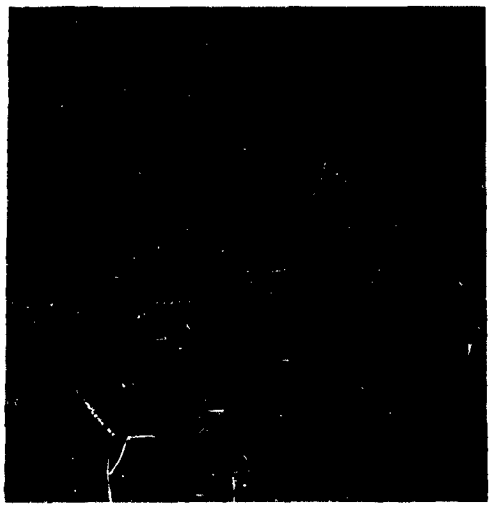
R12729 5AH 200X



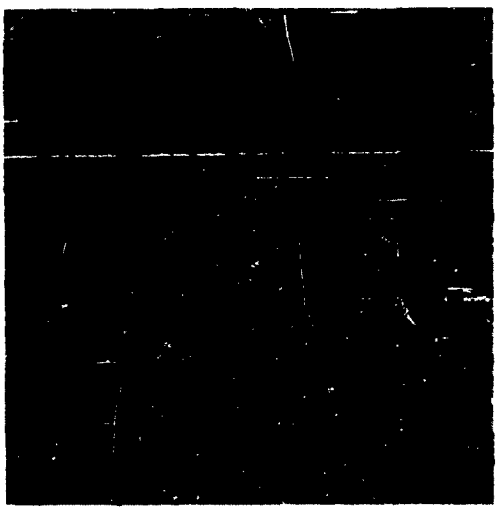
R12730 5BH 200X



R12735 4AH 1000X



R12736 4BH 1000X



R12737 5AH 1000X

R12738 5BH 1000X

SHEET TEST REPORT

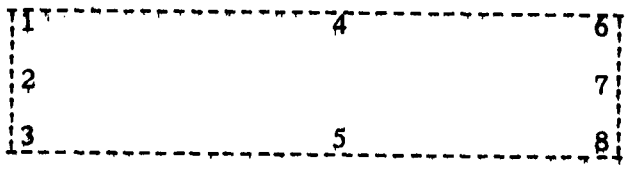
Alloy: Mo+.5%Ti
Producer: Universal-Cyclops Steel Corp.
Contract Number: NOas59-6142-c
Condition: Hot Rolled,Stress rlvd.Pkld.
Month and Year Produced: 11/62

Sheet Serial No.: 4A
Lot No.: T-2905
Heat No.: KD 1126B
Position in Ingot: Bottom
Sheet Size (Nom.)
Gauge: .060"
Length: 14"
Width: 36"

Visual Inspection:

Dimensional:

Length: 36-1/32"
Width: 14 to 14-1/16"
Camber: -
Thickness: 1 .0615" 2 .060" 3 .060"
4 .0625" 5 .061" 6 .0615"
7 .0605" 8 .061"



Flatness: 3%
Oil Can: -

Sonic: -

Chemistry of Sheet:

Alloy: 1 2 3 4
Impurity: 1 2 3 4
Interstitial: O N C H

SHEET TEST REPORT

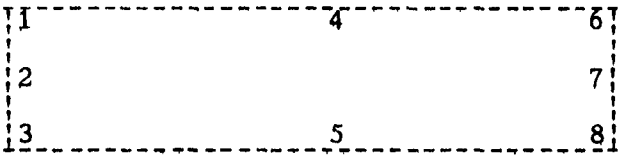
Alloy: Mo+.5%Ti
Producer: Universal-Cyclops Steel Corp.
Contract Number: NOas 59-6142-c
Condition: Hot rolled, stress rlvd, Pkld.
Month and Year Produced: 11/62

Sheet Serial No.: 5A
Lot No.: T-2905
Heat No.: Kd 1126B
Position in Ingot: Bottom
Sheet Size (Nom.)
Gauge: .060"
Length: 36"
Width: 14"

Visual Inspection:

Dimensional:

Length: 36"
Width: 14-1/16 to 14-1/8"
Camber: -
Thickness: 1 .061" 2 .0615" 3 .059"
4 .061" 5 .061" 6 .0605"
7 .060" 8 .059"



Flatness: 1 - 1/2%
Oil Can: -

Sonic: -

Chemistry of Sheet:

Alloy: 1 2 3 4
Impurity: 1 2 3 4
Interstitial: O N C H

SHEET TEST REPORT

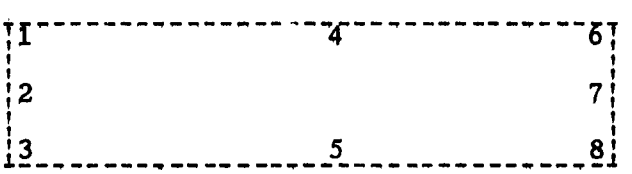
Alloy: Mo+.5%Ti
Producer: Universal-Cyclops Steel Corp.
Contract Number: NOas 59-6142-c
Condition: Hot rolled, stress rlvd, Pkld.
Month and Year Produced: 11/62

Sheet Serial No.: 5B
Lot No.: T-2905
Heat No.: Kd 1126B
Position in Ingot: Bottom
Sheet Size (Nom.)
Gauge: .060"
Length: 36"
Width: 14"

Visual Inspection:

Dimensional:

Length: 36" to 36-1/16"
Width: 13-15/16" to 14"
Camber: -
Thickness: 1 .061" 2 .061" 3 .060"
4 .061" 5 .060" 6 .061"
7 .059" 8 .058"



Flatness: 3-1/2%
Oil Can: -

Sonic: -

Chemistry of Sheet:

Alloy: 1 2 3 4
Impurity: 1 2 3 4
Interstitial: O N C H

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